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Saint Petersburg geothermal project

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ABSTRACT

The Saint-Petersburg geothermal project is developing for heat-supply system of the big greenhouse Complex A/S "Leto" near of international airport "Pulkovo". Geothermal gradient 0.03 °C/m was confirmed by exploration well, drilled trough 300-m sedimentary layers in granite-gneiss basement.

The first stage of the project creation includes five hydrofracturing zones (equiv. radius of 675 m between inclined (45°) intervals of injection and production wells on depth 2.2 km with rock temperature 75 "C, as upper reservoir of the cascade Geothermal Circulation System -GCS).. Total heat- exchange surface of 14 km^2 and water flow 0.2 m^3/sec guarantee 37.3 *MW* thermal power of hot-water supply system during 20 Years. Investments by our economic- mathematical model, with risk-factor 1.3, will be 5.6 M US$. In two Years of circulation with yearly production 1.072 M GJ the net profit is well to create, without bank credits, the second stage of cascade- deeper reservoir - 3 zones of hydrofractures (R_2= 790 m) on depth 3 km with temperature 95°C (2.5 M US$). Special wells construction allows to pass some part of flow rate with 70°C (after upper fractured zone) for overheating up to 90°C in deeper reservoir. Seasonal changing the overheating part of flow rate allows to rise the maximum thermal power of Cascade GCS from 37.3 up to 53.7 *MW*. Yearly production will be increased to 1.41 M GJ. After 3 Years (pay back time) clear cost of geothermal energy will be less then 1 US $ / GJ and the net production value- **NPV,** discounted for 20 Year, estimated about **28** M US$.

High level of economic efficiency connected with unusual high level of flow rate and thermal production. It became possible, thanking our new methods of fractures treatment (inside pressure 70 up to 360 MPa) for theirs aperture expansion to 3 - 5 mm. Pressure drops in fractures are **reduced** to 0.026 MPa and hydraulic impedance - to 0.26 MPa.s/l. Same flow rate and pressure drops possible to reach in case of natural reservoir with seam thickness 1.5 km and permeability not less, than 2 Darcy (unique case !).

The Saint Petersburg Project shows, that improving the hydrofracture treatment methods before circulation can guarantee effective heat mining from ***GCS*** with power of 50 - 60 MW per two wells even for case of moderate geothermal gradients.

KEYWORDS

Geothermal energy, Saint-Petersburg, hydrofractures treatment, impedance

1. Introduction

Main part of the geothermal energy, how it is known, is accumulated by solid hot rock. The technology of this petrogeothermal resources extraction is developing and testing already in more than ten Countries. That is a pity, but during more then two decades after the first brilliant demonstration by Los Alamos National Laboratory (LANL) this geothermal technology, using spacious hydrofkactures zones as a underground rock heat exchanger, have created or are testing in the USA, Great Britain, Germany, France, Japan, Sweden, Russia and others., but does not reach a commercial level.

The geothermal circulation systems (GCS) with such artificial reservoirs, in principle, can be created almost everywhere (certainly, with different economic results).

Another and more important preference of GCS that the depth (or rock temperature), dimensions and geometry of reservoirs, their permeability, hydraulic impedance and possible water flow rate - depend only on engineering decisions. High water flow rate W allows to get high level of thermal power N and the Yearly GCS production Q, which could be enough to "cover" consequence big investments and guarantee the positive economics.

However it is known [5], that demonstrate GCS in USA, Europe and Japan have (or had) W not more 20-30 l/s (excepting W_H=1 11 l/s during hydrofracturing operation for HDR-2 LANL). The main factor, limiting flow rate W, is too high hydraulic impedance I (up to 2 MPa.s/l), determinated by too small apertures δ of fractures and turbulence effects of inertial forces in high-velocity flow in near wells zones, in the first turn, - near production wells.

Some new methods of hydrofractures aperture expansion for impedance I decreasing and flow rate raising to improve GCS economics are discussing on example of the Saint-Petersburg geothermal project (SPGP).

On the south part of the Russian North capital and the adjoined regions by our geothennists doct. U.I. Moiseenko and oth. (All - Russian Geology Institute) proclaimed spacious zone of Thermoanomaly (more 13'000 km^2). At the big greenhouse combinate A.S. "Leto" (Pulcovo) drilled the first deep exploration well (1 km), which confiied depth-nature of this anomaly and allows sure to take the geothermal gradient g = 0.03°C/m. Of course, This is "anomaly" only for our cold north west regions. But in case of our Project will be successful even in such geothermal conditions, it would be very important example for other regions of the Russia and many other countries with moderate geothermal gradients.

2. Cascade circulation system of the SPGP

For the Saint-Petersburg Geothermal Project it is chosen the new variant of Cascade GCS (Russian Patent N 1420357 on 18 June 1988).

The Cascade circulation system has several distinctions. The first of them - two levels of artificial reservoir-upper and deeper (figure 1).

During the first stage of Project is creating only upper part of wells and reservoir: 5 vertical zones of hydrofractures (equivalent radius of each R_1 = 675 in) between of inclined intervals of injection and production wells on average depth H_1= 2200 m , virgin rock temperature T=75°C. Diameter of wells is taken d=0.254 m and water flow rate W = 0.2 m^3/s, thermal power of GCS N_1 = 37.3 MW. Consumer (A.S."Leto") obtains from the heat-exchanger on the surface hot water with T_1 = 70°C and uses it to T_0= 25°C.

Total heat-exchange surface of upper reservoir fractures F_1=14.3 km^2 was determinate by our criteria dependence, obtained from the numerical computer's simulation of processes [2,3], and together with volume of cooling rock (interval 30 m between fractures zones) guarantee indicated levels of T_1 and N_1 of whole-year hot water supply of consumer during the service life t_c=20 Years. Evident preference of Cascade is reduction to minimum the initial investments (4.8-5.6 M US$) and the time of construction without production, because T_1=70°C is not enough for consumer only in 2-3 cold months..

More of that. During the first 3 years of operations the profit of production will be enough not only to pay back the bank credits and interest, but also to create the second stage GCS (ΔK=2.5 M US$): the additional drilling of both wells and hydrofracturing of 3 zones (Rz = 790 **in,** F_2 = 11.7 km^2) for the deeper part of reservoirs on average depth H_2 = 2960 in with T_2= 95°C, increasing of GCS thermal power to N_2 = 53.7 VW and Q_Z = 1.41 . 10^6 GJ/Year.

The second feature of Cascade GCS is connected with seasonal (or any other) changing **of** the thermal parameters T, and N. If it is necessary to obtain hot water with temperature T, > T_1, some part AW of total flow W, after heating in upper reservoirs up to T_1=70°C, directs through internal pipeline (d_2≈0.15 m) inside injection well to deeper reservoir for overheating. This fraction of W depends on temperature T,, prescribed by consumer:

$$\Delta W = W \frac{Tc - T_1}{T_2 - T_1} \qquad (1)$$

Changing AW by turn of valve, it is possible to raise the temperature of mixture flow from T, = T_1 (ΔW=0) up to T_c= T_2 (ΔW=W). It is quite understandable, the very complicate thermoinertial effects in circulation system can't disturb to this hydromechanical manner of the temperature control.

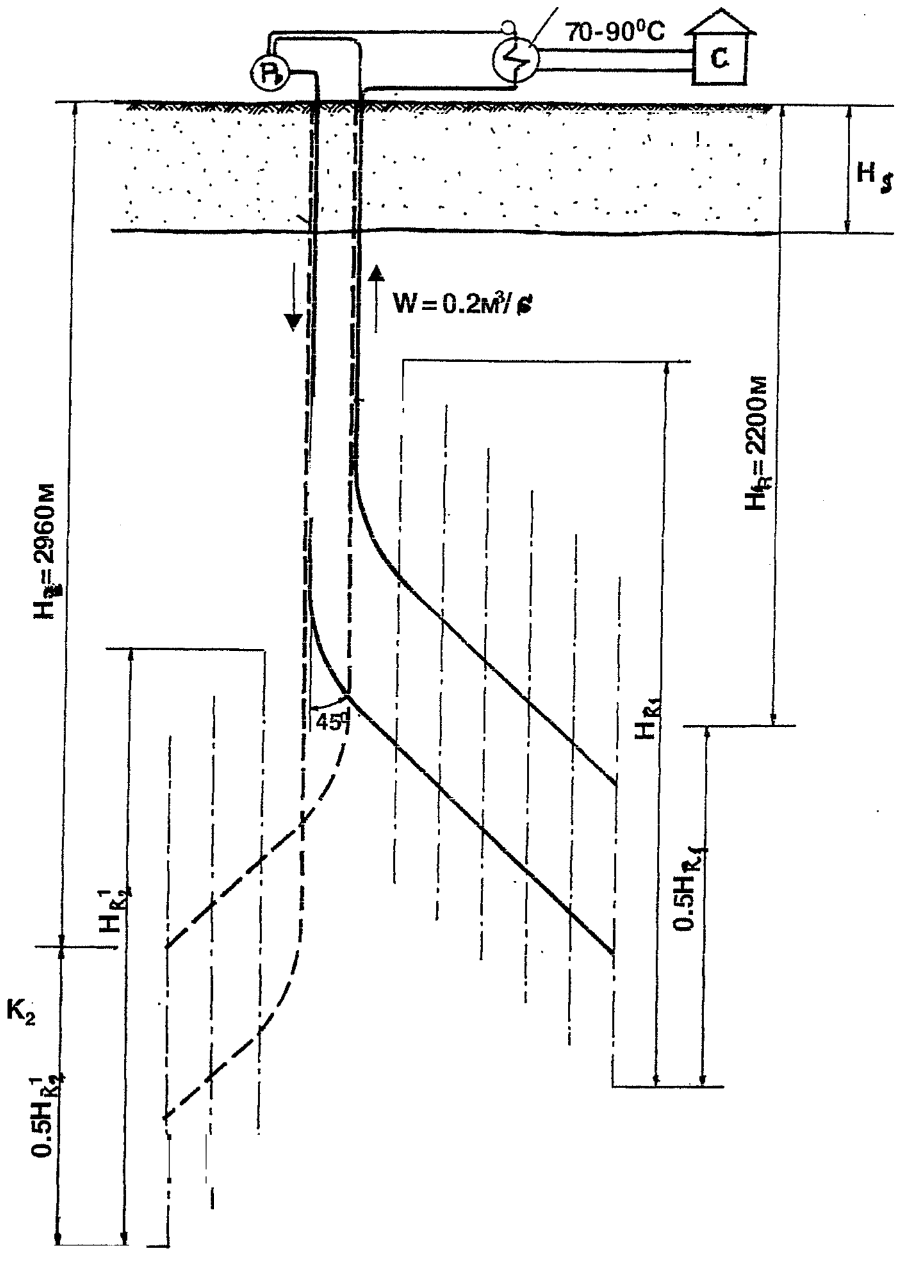

Figure 1: Saint-Petersburg geothermal project. Cascade circulation heat supply system of A/S "Leto" Pulcovo

3. Model and parameters of geothermal hydrofractures

The initiation and expansion of hydrofractures in three-dimension tectonic-gravital stressed field of hot rock mass our physical model are considering as the coupled thermo-hydro-geomechanical processes [1, 3]. Naturally, this is based on the classical decision by I.Sneddon and oth. for some ideal homogenous isotropic and linear-elastic continuum, but takes into account the characteristic properties of real rock mass, geometry of its joints structure, strong influence of tectonic stress and thermodeformations, weakness effects from active compressive stress on tensile strength in plane (by **A. Griffith** equation) and volume deformations near the contour of growing fracture, inertial effect of turbulent flow in fracture's zones near wells and others.

The most probable mechanism of hydrofracture is determinated by minimum variant of the water pressure P_H on the fracture contour before next jump-like fracture growth from comparison of four of possible tensile and shear deformations The opening of tectonic joints P_{Hn} can be most probable in case of sub-vertical joints are oriented normally to minimum horizontal stress σ_x. Competitive mechanism for this conditions can be the shear along this joints P_{HS}.

For the other cases is possible the formation of vertical fracture, intersecting rock blocks normally to σ_x (P_{HV}). Shear fracture along any another direction has few chances.

The most important parameter δ -average aperture of magistral fracture is definated as:

$$\delta = \frac{0.128}{F_1} \cdot \sqrt[4]{\frac{(1-\nu)\rho_W^2 W_H^3 k_\delta}{0.5 G Re^* d\mu}} + 2\alpha_T E_W \Delta T \sqrt{at} \qquad (2)$$

where ν and G, a and α_T - Poisson ratio and shear module, Thermal diffusivity and thermal expansion of rock; ρ_W, μ, E_W and W_H - density, viscosity, elasticity module of

working liquid - water and rate of its pumping; $Re^* = 1500$ - critical Reynolds number [1], ΔT - average "rock-water" temperature differences; t - time of hydrofracturing duration; F_i - function of inertial effects **[3]** and k_δ - coupled function:

$$k_\delta = 1 + \frac{\Delta P_S - \Delta P_T}{F_i \Delta P_L} \qquad (3)$$

ΔP_S - mechanical resistance - strength, taking of structure and compressive weakness effects;

ΔP_L - hydraulic pressure drops for laminar flow in main part of fracture (from known Dupuit's equation);

ΔP_T - raising of pressure due heating water flow thermal expansion - by experimental dependence [3].

For jointed rock mass with average permeability k, piezoconductivity χ, porous (joints) liquid pressure P_P clear pumping time of hydrofracturing zone jump-like expansion to proposed square of R_{fr} will be:

$$t = \left[\frac{2\pi R_{fr}^2 \, k(P_H - P_T)}{2.7 W \mu \sqrt{\chi}} \right]^2 \qquad (4)$$

For the known conditions and results of LANL experiment 2032 the fracture aperture near injection well $\delta_0 = 2.3$ mm and the pumping t = 61 hours [3]. In case of maximum rate of pumping W=111/s by (2) it is obtained $\delta_0 = 6 F_i = 2.5$ mm, for average rate W = 97.6 l/s, $\delta_0 = 2.2$ mm and time of pumping by (4) t = 63.5 hours. Calculated sizes of fractures zone, depth of filtration leakage and total volume of water pumped by our model also near to experimental data [3].

In case of our project calculated aperture of fracture near injection well $\delta_0' = 2.38$ mm and near production well 60= 0.38 mm . It is obvious, that to pass designed flow rate W = 0.2 m^3/s through such fractures system practically impossible (the pump's pressure must be 98.6 MPa with N_p = 30 MWe) . Therefore our Project includes several (2 - 3) physical treatment of each near-well zones of reservoir before circulation. This partly patented new methods of fractures high - pressure treatment using reversing of flow and include two-phase viscosity foam pumping (30 - 70 MPa), thermo-gasedynamic treatment (200 - 250 MPa) and water inside fracture freezing by solid carbon dioxide - "dry ice" or liquid nitrogen (up to 360 MPa) . This complex of treatment can expanse near well zones of fractures up to 4.5 - 4.9 mm for reduction of reservoir's pressure drops to 0.48 - 0.25 MPa, hydraulic impedance - to 0.023 MPa.s/l and guarantee of circulation energy consumption to thermal production ratio (in oil equivalent) - to level of 1/12.

4. Economic analysis

Our GCS economic - mathematical models (EMM) "Fracture" and "Geothermy" include the algorithm of the hydrofracturung and fracture's treatment processes, partly reflected in chapters by J. Tester and H.Herzog: Statistic economical dependencies full cost of well on its length [5, 2522p.], taking into account of E.Boguslavsky's empirical depend it on well diameter [5, p.2844], also inflation raising of costs during the period of 1990 to 1999.

The initial investments for the first stage of the project estimated with risk factor 1.3 as 5.6 M US$ (wells, hydrofractures, treatment) of the upper reservoir and surfaces equipment complex/The pay back period is taken 3 years and includes creation the second stage of Project (2.5 M US$) using profit, without bank credit. Beginning of 4-th years of operation clear cost of geothermal energy will be near 1 US$/GJ and total, discounted for 20 years of service life the Net Value Production calculated as NPV = 28 M US$ [4].

From computer analysis of EMM is obtained the correlation dependents of full cost of production on most important parameters W and d for case of g = 0.03 °C/m [4].

$$c_T = 0.0126\ W^2\ d^{-5.25} + (d^{1.1}) / W + \mathbf{0.97},\ \text{US\$/GJ} \qquad (5)$$

Using (5) for any diameter is possible to find the optimal flow rate:

$$W_{opt} = 3.01\ d^{2.12},\ m^3/s \qquad (6)$$

5. Conclusions

Our long term geothermal research, including Tyrniaus (near Elbrus, North Caucasus) experimental hydrofracture of hot granite (near 4 km, 210°C), laboratory and polygon testing some fracture's treatment methods and computer analysis allow to underline the next principal consequences:

Before development of hot rock energy mining reaches to commercial level, geothermal fraction in the world energy balance can't be essential.

The big scale hydrofracture of hot rock in several countries confirmed, that it is certain technology to create the rock heat exchanger's of indispensable dimensions 1.5 - 2 km^2. But the aperture of this artificial fracture's as a rule too small and high hydraulic impedance allows to pass water flow rate not more 10 - 30 **l/s,** which could be profitable only with temperature over 200 - 300°C, that is again for the rarely local volcano anomaly.

Expansion of hydrofractures aperture before to circulation can guarantee to raise of water flow rate up to 200-300 l/s = 0.2 - 0.3 m^3/s with thermal power on pair of well to 30 - 50 MW, when geothermal energy using could be economic efficiency even in regions with usual moderate gradient. ***So,*** improving of the fractures expansion methods is one from the most important problems of geothermal technology farther development.

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